USE OF SHUNT RESISTOR WITH LARGE RA PRODUCT TUNNEL BARRIERS

Technical Field

The present invention relates to storage devices. In particular, the present invention relates to a tunnel valve read head for a disk drive that minimizes the effective device resistance R_D and improves the device Signal-to-Noise Ratio (SNR).

Background of the Invention

Figure 1 shows an exemplary high-RPM disk drive 100 having a magnetic read/write head (or a recording slider) 101 that includes, for example, a tunnel-valve read sensor, that is positioned over a selected track on a magnetic disk 102 using, for example, a two-stage servo system for reading data stored on disk 102. The two-stage servo system includes a voice-coil motor (VCM) 104 for coarse positioning a read/write head suspension 105 and may include a microactuator, or micropositioner, for fine positioning read/write head 101 over the selected track.

A problem associated with tunnel-valve read sensors is that achievable values of the resistance-area (RA) product for tunnel junctions having large and/or optimized Tunnel Magneto-Resistance (TMR) values (i.e., $\Delta R/R_0$) are too large for achieving a desirable device resistance R_D of less than approximately 300 Ohms for device areas A_D that are smaller than 0.1 μm^2. The motivation for a lower device resistance R_D is primarily for increasing the signal power ($\propto (\Delta R/R)^2 (V_{bias})^2 / R_D$) while simultaneously reducing the shot-noise of a tunnel-valve head ($\propto R_D$) when operated at a given bias voltage V_{bias}, which is otherwise limited by additional considerations that are described below. A secondary consideration is for avoiding excessive device impedance mismatch with the characteristic impedance Z_0 of the transmission line interconnection to the Arm Electronics (AE) module, which is typically less than or equal to 100 Ohms. A mismatch has the effect of increasing amplifier noise. Accordingly, constraining $R_D = (RA)/A_D$ to be less than 300 Ohms requires RA to be greater than 1-2 Ohms-μm^2.

Figure 2 is a graph 200 showing the approximate relationship between RA and $\Delta R/R_0$ for a typical tunnel junction in which RA and $\Delta R/R_0$ are respectively the abscissa

and the ordinate of graph 200. As RA is reduced below a "corner" value of RA_c by reducing the physical barrier thickness, the low-voltage TMR ratio $\Delta R/R_0$ begins to degrade approximately linearly as RA decreases. Tunnel valve barriers typically exhibit an RA_c value of approximately 5-10 Ohms-μm^2. Thus, the achievable $\Delta R/R_0$ for an $RA < 1\text{-}2$ Ohms-μm^2 will be significantly below the maximum value of $\Delta R/R_{max}$ that is obtainable for thicker, higher-RA barriers of the same barrier material. Reducing RA by decreasing barrier thickness also results in barriers that are less physically robust and that are more susceptible to pinholes and/or other run-to-run variabilities that can yield large distribution of both $\Delta R/R_0$ and RA values across a wafer and/or from wafer-to-wafer. Such variations are much less prevalent when thicker tunneling barriers having $RA \geq RA_C$ are used.

Additionally, it is well known that the TMR ratio is not independent of the bias voltage, but instead decreases monotonically with larger V_{bias}. Figure 3 is a graph 300 showing a typical $\Delta R/R$ for a tunneling barrier as a function of V_{bias}. As shown in Figure 3, $\Delta R/R$ decreases approximately linearly with increasing $V_{bias} \leq V_{50}$, in which V_{50} is the value of V_{bias} for which the TMR ratio $\Delta R/R$ has degraded to one-half of its low voltage limit. For this reason alone, it becomes impractical to operate tunnel-valve read sensors at bias voltages larger than V_{bias}. Long-term degradation, however, usually limits the practical barrier bias voltage V_{bias} to well below the V_{50} value. Depending on the barrier material, V_{50} also tends to degrade for thinner, lower-RA barriers, and is, at best, approximately constant with $RA \leq RA_c$.

What is needed is a technique that minimizes the effective device resistance R_D of a tunnel valve read head and improves the device Signal-to-Noise Ratio (SNR) of a tunnel valve read head.

Summary of the Invention

The present invention minimizes the effective device resistance R_D of a tunnel valve read head and improves the device Signal-to-Noise Ratio (SNR) of a tunnel valve read head.

The advantages of the present invention are provided by a read head for use with an interconnect transmission line having a characteristic impedance of Z_0. The read head

includes a tunnel valve device and a shunt resistance R_S. The tunnel valve device has a device resistance R_T corresponding to a predetermined resistance-area (RA) product. The shunt resistance R_S is connected in parallel across the tunnel valve device. The value of the shunt resistance is chosen such that the parallel combination of R_T and R_S substantially equals a predetermined selected value of resistance, such as the characteristic impedance Z_0 of the interconnect transmission line. According to one aspect of the present invention, the predetermined resistance-area (RA) product is about equal to at least about 10 Ohms-μm^2. According to another aspect of the present invention, the predetermined resistance-area (RA) product is about equal to a value of a resistance-area (RA) product in which a Tunnel Magneto-Resistance (TMR) ratio $\Delta R/R_0$ for the tunnel valve device does not substantially increase for further increase in the value of the resistance-area (RA) product.

Brief Description of the Drawings

The present invention is illustrated by way of example and not by limitation in the accompanying figures in which like reference numerals indicate similar elements and in which:

Figure 1 shows an exemplary high-RPM disk drive having a magnetic read/write head;

Figure 2 is a graph showing the approximate relationship between RA and $\Delta R/R_0$ for a tunnel junction;

Figure 3 is a graph showing a typical $\Delta R/R$ for a tunneling barrier as a function of V_{bias};

Figure 4 shows an equivalent circuit schematic diagram of an MTJ sensor valve, a head-to-AE interconnect transmission line and an AE preamplifier; and

Figure 5 is a graph showing the ratio of SNR_2:SNR_1 as a function of R_D for several values of V_{bias}.

Detailed Description of the Invention

The present invention provides minimizes the effective device resistance R_D of a tunnel valve read head and improves the device Signal-to-Noise Ratio (SNR) of a tunnel

valve read head. The shunt resistor R_S is preferably fabricated directly on the substrate/slider using standard deposition and photolithographic techniques, although the shunt resistor could also possibly be supplied externally as part of the AE module. A tunnel valve head can be designed using the shunt resistor R_S of the present invention for a given targeted device area A_D and resistance R_D, while simultaneously fabricating the tunnel valve barrier to have a much more physically robust thickness in which $RA \approx RA_c$, despite that the intrinsic tunnel sensor resistance $R_T = RA_c/A_D$ may significantly exceed R_D. The present invention minimizes the effective device resistance R_D of a tunnel valve head without excessively compromising signal/noise ratio (SNR) and device robustness relating to device yield, wafer variability, and long-term reliability.

Figure 4 shows an equivalent circuit schematic diagram 400 of an MTJ sensor valve 401, a head-to-AE interconnect transmission line 402 and an AE preamplifier 403. MTJ sensor valve 401 includes tunnel valve sensor resistance R_T and shunt resistance R_S. As shown in Figure 4, MTJ sensor valve 401 is modeled to include a signal voltage S_T and/or a noise source N_T. Shunt resistance R_S is modeled to include a noise source N_S. Preamplifier 403 is modeled to include rms voltage noise source V_A and current noise source I_A. Additionally, the input impedance of preamplifier 403 is assumed to be equal to the characteristic impedance Z_0 of interconnection transmission line 402 so that both the rms signal voltage S_T and rms noise voltage N_T of MTJ sensor valve 401 are transmitted to preamplifier 403 without reflection.

The expected voltage signal power of the MJT sensor valve S_D^2 is given by,

$$S_D^2 = (Z/R_T)^2\, V_{bias}^2\, (\Delta R/R)_0^2 \left(1 - \frac{1}{2}\left|V_{bias}/V_{50}\right|\right)^2, \tag{1}$$

in which

$$Z = R_D \parallel Z_0 \tag{2}$$

and

$$R_D = R_T \parallel R_S \tag{3}$$

The noise power N_D^2 at the input to preamplifier 403 is given by

$$N_D^2 = \left|\frac{Z}{R_T}\right|^2 4kTR_T \left\{\frac{V_{bias}}{V_{th}} \coth\left(\frac{V_{bias}}{V_{th}}\right)\right\} + \left|\frac{Z}{R_S}\right|^2 4kTR_S\,, \tag{4}$$

in which

$$V_{th} = 2kT / e \cong 60\ mV \tag{5}$$

The expressions for both S_D^2 and N_D^2 include the shunting effects of both the shunt resistor R_S of the present invention, as well as that of the preamplifier input impedance Z_0. The expression for the noise power N_D^2 includes the shot noise plus the Johnson noise for the tunnel valve, in addition to the Johnson noise for the shunt resistor R_S. (For simplicity, this expression excludes the noise due to the current and voltage noise of the amplifier which depend on the reflections at the impedance-mismatched interface between transmission-line and read sensor.) For bias voltages that are expected between 100-200 mV, the shot noise power for the tunnel valve substantially exceeds the Johnson noise $4kTR_T$ for the tunnel-valve device, as well as and the Johnson noise $4kTR_S$ for a comparable shunt resistance, and varies essentially linearly with V_{bias}. The expression for signal power S_D^2 explicitly includes the dependence on $\Delta R/R(V_{bias})$, which is shown in Figure 3, but only implicitly includes the dependence of $\Delta R/R_0$ on the RA product of the tunnel barrier, which is shown in Figure 2. The dependence of $\Delta R/R_0$ on the RA product of the tunnel barrier is of key importance because signal power varies as $(\Delta R/R_0)^2$.

To emphasize the importance of the dependence of $\Delta R/R_0$ on the RA product of the tunnel barrier, the signal and noise expressions are used for computing the signal/noise ratio SNR as

$$SNR = \frac{S_D^2}{N_D^2} \tag{6}$$

for a conventional tunnel-valve head and for a tunnel-valve head having a shunt resistance R_S according to the present invention for a design target device resistance R_D and a design target device area A_D. For the conventional tunnel-valve head design, there is no shunt resistor (i.e., R_S goes to infinity), and the tunnel barrier thickness is chosen such that the RA product of the barrier is

$$RA_1 = R_D A_D. \tag{7}$$

For the a tunnel-valve head design having a shunt resistance R_S according to the present invention, the tunnel barrier thickness is increased such that

$$RA_2 = RA_c, \tag{8}$$

i.e., the value at the "corner" of the $\Delta R/R_0$ vs. RA curve shown in Figure 1. The head resistance of the tunnel valve is then

$$R_T = \frac{RA_c}{A_D} \tag{9}$$

and the shunt resistor R_S is then chosen such that the parallel combination of R_T and R_S $(R_T \parallel R_S)$ equals the target device resistance R_D. That is,

$$R_S = R_T R_D / (R_T - R_D). \tag{10}$$

It is naturally assumed that $R_D \leq R_T$ because, otherwise, shunt resistor R_S becomes superfluous.

For comparison purposes, the following parameter values will be assumed: $A_D = 0.005\ \mu m^2$, $V_{50} = 400$ mV, $RA_C = 10$ Ohms-μm^2, and $Z_0 = 75$ Ohms. In this case, the intrinsic sensor resistance of a thick barrier with $RA = RA_C$ would be an excessively large $R_T = RA_C/A_D = 2000$ Ohms. The characteristic "thermal voltage" $V_{th} = 2kT/e$ (50 mV at room temperature) is taken to be 60 mV.

Figure 5 is a graph showing the ratio of $SNR_2:SNR_1$ as a function of design target device resistance R_D for several values of V_{bias}. In Figure 5, SNR_1 is the SNR for a conventional tunnel-valve head and SNR_2 is the SNR for a tunnel-valve head having a shunt resistance R_S according to the present invention. As shown in Figure 5, the ratio of $SNR_2:SNR_1$ increases as R_D decreases. The two designs are equivalent when $R_D = 2$ kOhms. In the case of a more desirable design target resistance of $R_D = 300$ Ohms, a significantly greater intrinsic sensor signal/noise ratio (i.e., 3-4 dB excluding amplifier noise) can be achieved with the present invention by using a physically robust $RA = 10$ Ohms-μm^2 barrier combined with shunt resistor $R_S = 350$ Ohms. In contrast, a conventional tunnel-valve head design requires that a thin tunnel barrier be fabricated having a very low value of RA = 1.5, and having an expected 85% TMR loss of $\Delta R/R_0 = (RA/RA_C = 0.15)\ \Delta R/R_{max}$ for the same design target resistance of $R_D = 300$ Ohms. The comparative SNR advantage of the present invention

increases as the target device resistance R_D is further reduced and/or bias voltage V_{bias} is increased.

Generally, the advantages of the present invention are related to the dependence $\Delta R/R_0$ on RA, as shown in Figure 2. Provided that $RA \leq RA_c$, $\Delta R/R_0$ scales approximately as RA, while R_T scales as RA for a fixed A_D. Thus, $\Delta R/R_0$ scales approximately as R_T. For typical parameter values for the circuit of Figure 4 in which $Z_0 \ll R_T, R_S$, such that $Z \approx Z_0$, S_D^2 becomes roughly independent of R_T, but N_D^2 scales as $1/R_D + 1/R_T*[V_{bias}/V_{th} \coth(V_{bias}/V_{th}) - 1]$. Thus, for a fixed target R_D, noise power is reduced and SNR increased by increasing intrinsic R_T. Noise power is further reduced and SNR is further increased as V_{bias} increases, particularly when $V_{bias} \gg V_{th}$, which is expected to be the case in practice. At very low R_D approaching Z_0, which in the unshunted (conventional) case $R_D = R_T$, S_D^2 additionally begins to decrease with reduced R_T, and the SNR advantage of the shunt resistor of the present invention accelerates, a trend that is also evident in Figure 5. Finally, the advantage in intrinsic sensor SNR provided by the present invention is not based on any additional benefit of a potential increase in V_{50} and/or safe and stable maximum operating bias voltage when using a higher R_T, physically thicker and more robust tunnel barrier afforded by the present invention.

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced that are within the scope of the appended claims. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.